JOINT INVERSION OF RECEIVER FUNCTIONS AND SURFACE-WAVE DISPERSION FOR CRUSTAL STRUCTURE

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ABSTRACT

Teleseismic P-wave receiver functions and surface-wave dispersion measurements can be employed to simultaneously infer the shear-wave velocity distribution with depth in the lithosphere. Receiver functions are primarily sensitive to shear-wave velocity contrasts and vertical travel times and surface-wave dispersion measurements are sensitive to vertical shear-wave velocity averages, so that their combination bridges resolution gaps associated with each individual data set.

The inversions are performed using a joint, linearized inversion scheme which accounts for the relative influence of each set of observations, and allows a trade-off between fitting the observations and the smoothness of the model. Additional constraints on mantle structure are also incorporated during the inversion procedure since requiring the data to blend smoothly into an appropriate deep structure affects the estimate of the lower crust velocities, yielding models which are more consistent with expectations than those resulting from unconstrained inversions. We have found that *a priori* knowledge of upper mantle velocities are required to predict the dispersion up to 50 sec period and that stability constraints are required. When dispersion is limited to periods grater than 15 sec *a priori* information on the upper crustal velocities may also be required.

Results of applying this technique to data from different tectonic environments in the Arabian Plate and North America will be presented.

OBJECTIVE

The object of this effort is to implement an efficient algorithm for jointly inverting receiver functions and surface wave dispersion velocities to constraint shear-wave velocity with depth. The benefits of this joint inversion have been shown by several authors [Ozalaybey et al., 1997; Du and Foulger, 1999; Julia et al, 2000]. When no noise is present, the complementary constraints in receiver functions and dispersion observations uniquely characterize the shear-wave velocity variation with depth. Dispersion observations are sensitive to absolute vertical shear-wave velocity averages and the receiver functions are primarily sensitive to shear-wave velocity averages and vertical travel times. Their joint inversion give rise to models where the details constrained by the receiver functions are superimposed to a background velocity model constrained by the dispersion measurements. When noise is contaminating the data the constraints on the model parameters become incompatible, since the noise independently distorts the model imaged by both receiver function and dispersion measurements. The joint inversion, therefore, helps to avoid overinterpreting the data as a result of over-fitting either data set noise.

The utility of this approach in a CTBT framework is that the crustal structure beneath seismograph stations can be assessed. As CTBT monitoring stations are installed, teleseismic waves can be recorded and receiver functions obtained during the initial operation. These estimates together with preexisting dispersion measurements [e.g. Ritzwoller and Levshin, 1998] allow a rapid application of the proposed methodology, so that the S-velocity structure beneath the station can be inferred in the short run. One of the difficult tasks is then assessing estimates of the earth structure models. As in all science the consistency of independent work lends confidence to a result. Some examples are shown below for the Arabian Shield where we

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compare velocity models estimated from the joint inversions with those from refraction surveys [Mooney et al., 1985; Prodehl, 1985; Badri, 1991].

Further verification of model suitability is the direct estimation of source properties or construction of phase-match filters using the constructed velocity structures. We believe that this localized structures will permit waveform inversion of regional signals for source identification and will help to produce more accurate filters for signal identification and enhancement, and eventual source identification.

RESEARCH ACCOMPLISHED

We employ a "jumping" algorithm to jointly invert receiver functions and surface-wave dispersion observations for shear-wave velocity. The jumping scheme allows us to implement smoothness constraint in the inversion by minimizing a model roughness norm [Constable et al., 1987] that trade-off with the goodness of fit. Our design of goodness of fit criterion [Julia et al., 2000] takes into account the different units, magnitudes, noise and number of observations of the data and allows to set an influence parameter 'p' before inversion to balance the relative importance of each data set of observations. In particular, a value of p=0 only uses the receiver function data and a value of p=1 only uses the dispersion data.

The system of equations to be inverted is given by

$$\begin{pmatrix} pD_s \\ qD_r \\ sA \end{pmatrix} \vec{x} = \begin{pmatrix} \vec{r}_s \\ \vec{r}_r \\ 0 \end{pmatrix} + \begin{pmatrix} D_s \\ D_r \\ 0 \end{pmatrix} \vec{x}_0$$

where D_s and D_r are the partial derivative matrices for the dispersion measurements and the receiver function estimates, respectively, $\vec{r}_s$ and $\vec{r}_r$ are the corresponding vectors of residuals, $\vec{x}$ is the vector of S-wave velocity, $\vec{x}_0$ is the starting model, and A is a matrix that constructs the second order difference of the model $\vec{x}$. The factor q equals $1-p$ and the factor s balance the trade-off between data fitting and model smoothness.

Additional constraints for upper mantle structure

Additional *a priori* information is required to stabilize the results of our models in the upper mantle. One possibility is to require the deepest layers in our model to be similar to predetermined values, such as PREM. This can be achieved by adding the following set of equations to the original system (1) [Jackson, 1972]

$$W\vec{x} = W\vec{x}_a$$

where $W = (w_{ii})$ is a diagonal matrix of weights and the vector $\vec{x}_a$ contains the *a priori* predefined velocity values. Figure 1 is a comparison between the data only inversion and the velocity constrained inversion for station SODA, in the Arabian Shield, the constraints consisting of forcing our inverted velocity values to be PREM below 55 km depth. The predicted receiver functions are almost unchanged as well as the predicted dispersion velocities at short periods. The sensitivity of the long period range to mantle structure is an important point, since requiring our data to blend smoothly into a more appropriate deep structure affects our estimate of the lower crust velocities. Therefore, it is important to insure a reasonable upper mantle in the model, not allow the inversion to place an unusual and unlikely structure and simply ignore it because it is unresolved. This example has implications for all narrow band studies of structure.

Application to the Arabian Shield

We employ the methodology described in the preceding section to model receiver functions estimated in the Saudi Arabian Broadband Deployment stations (Figure 2) jointly with group velocities for the fundamental mode of Rayleigh and Love waves, as inferred from an independent tomographic study carried out by Mokhtar et al. [2000]. Receiver function estimates at two overlapping frequency bands are inverted at the same time, jointly with the dispersion observations, to allow a better examination of the transition zones within the structure [Cassidy, 1992]. The data allow analysis to be performed using waves approaching the stations at two different backazimuths, so that evidence for lateral variation is investigated as well. Figures 3, 4 and 5 show the receiver function fits, dispersion velocity fits and resulting models, respectively. In general all the models contain a rapid velocity increase during the few first kilometers below the surface, a lower crust with a rather constant velocity, and a gradational crust-to-mantle transition.

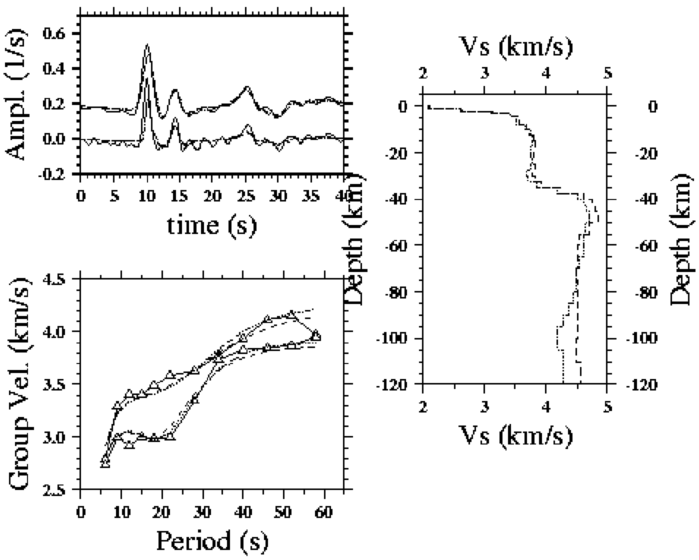


Figure 1: Comparison between the data-only and the constrained inversion results for receiver functions (upper left), dispersion velocities (lower left) and resulting models (right) at station SODA. Solid, dotted and dashed lines correspond to observations, data-only inversion and constrained inversion, respectively.

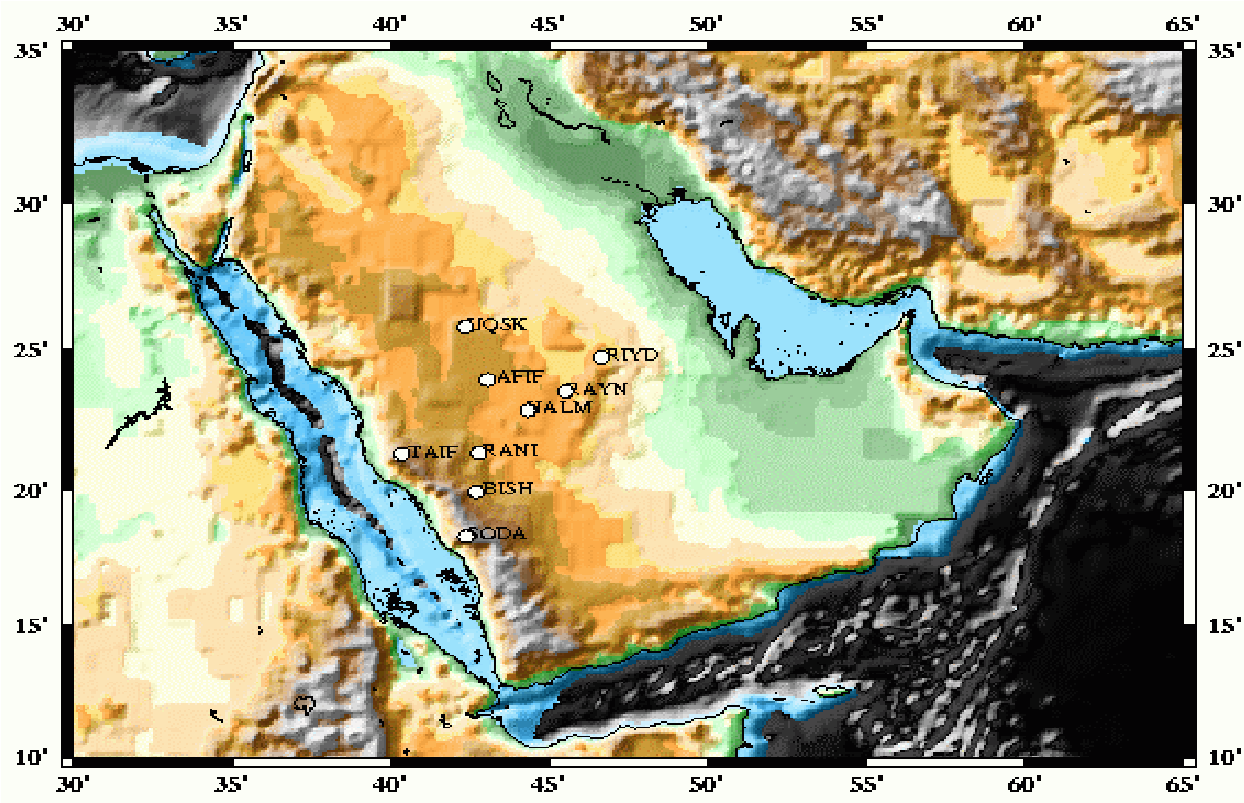
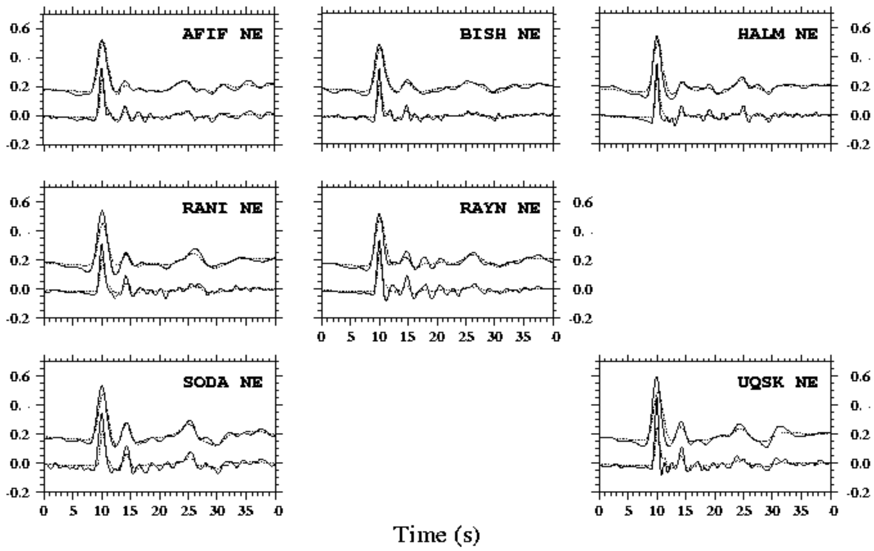


Figure 2: Topographic map of the Arabian Peninsula showing the location of the temporary broadband stations.



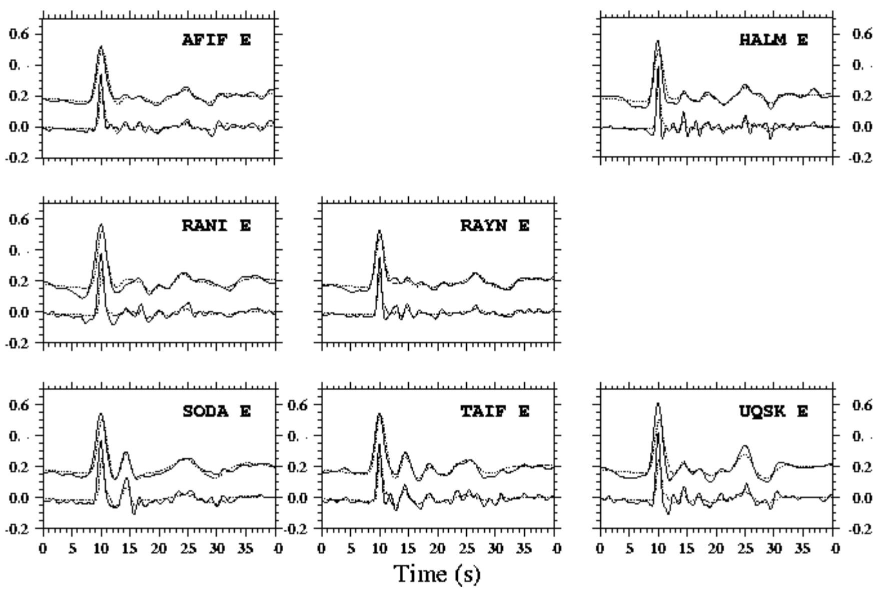


Figure 3: (top) Receiver function waveforms for events approaching NE of the station. (bottom) Receiver function waveforms for events approaching E of the station. Solid and dashed lines are observed and predicted receiver functions, respectively. The station code is shown in the upper right corner.

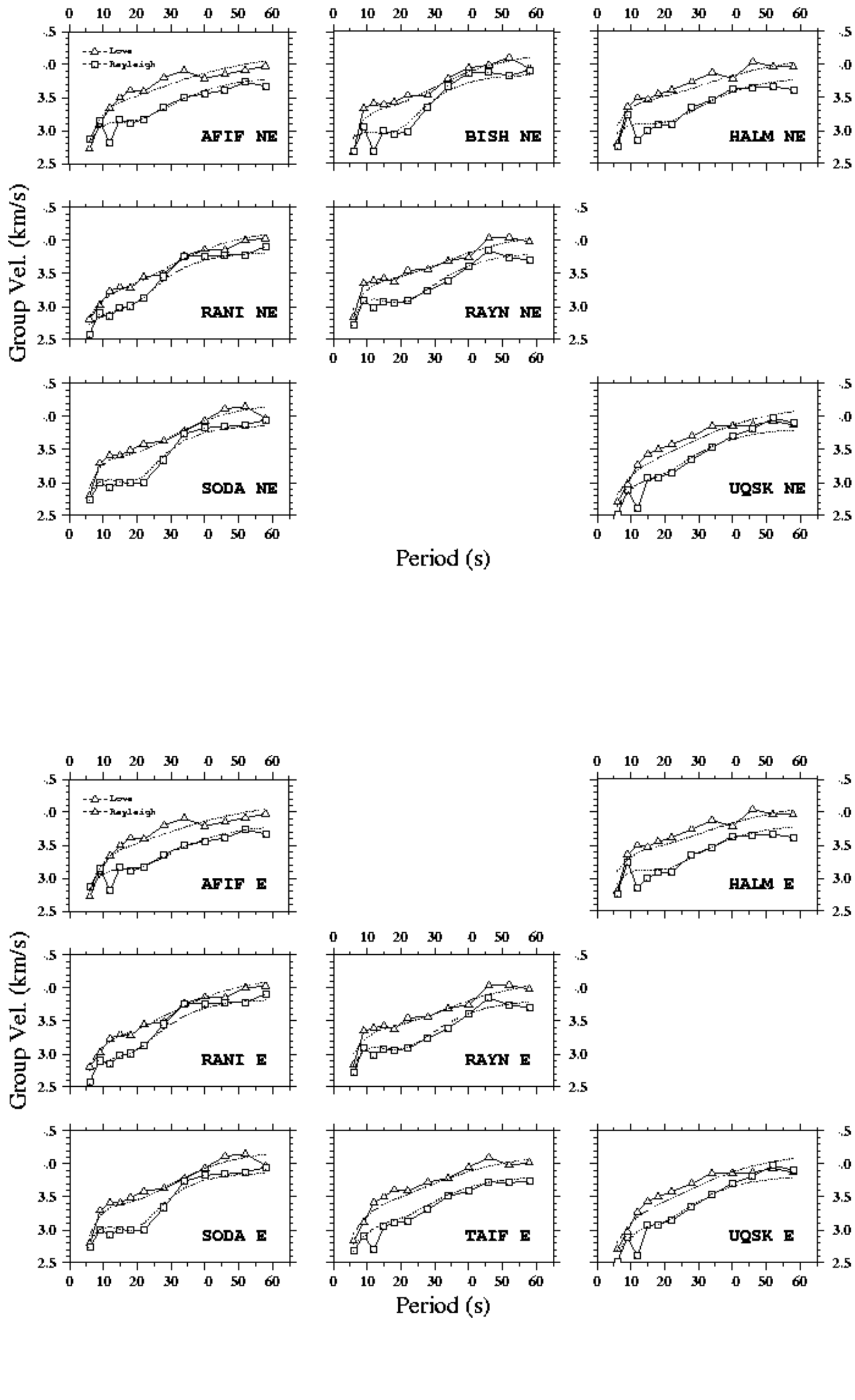


Figure 4: Observed (solid) and predicted (dashed) group velocities at temporary stations in the Arabian Peninsula from the inverted models obtained jointly with the NE (top) and E (bottom) receiver function waveforms. Station codes are labeled in the lower right corner.

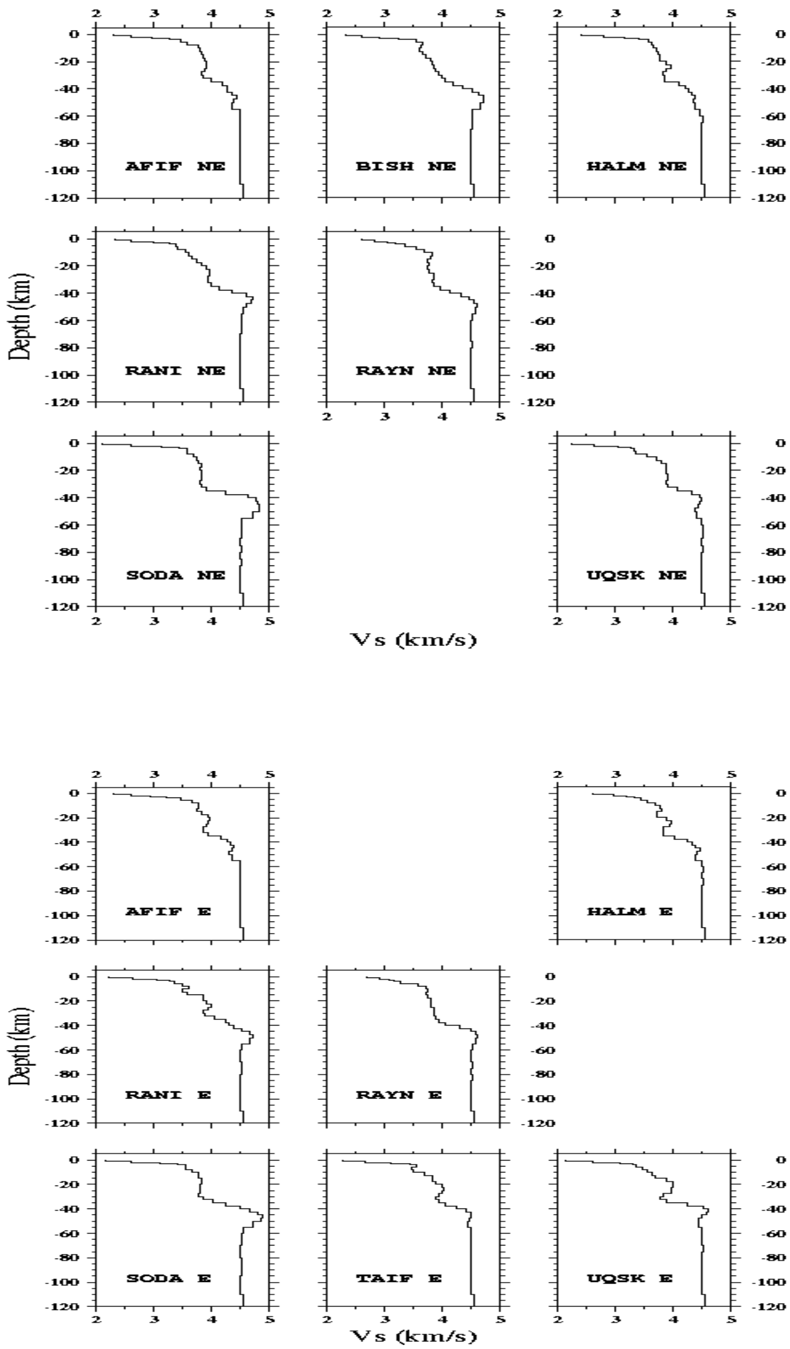


Figure 5: Resulting models obtained from the combination of the dispersion group velocity values and the NE (left) and E (right) receiver functions.

We compare the NE models to the interpretive crustal sections provided by Mooney et al. [1985], Prodehl [1985] and Badri [1991] (Figure 6), by assuming a Poisson's ratio of 0.25. In general our upper mantle is slower, and no one

of the two contrasts inferred in the Mooney et al. [1985] refraction model observed in ours. The upper mantle constraints imposed to our models could be masking such features and could be leading to underestimated velocity values; however, we cannot see strong evidence of such contrasts in our receiver functions and the fit to the high period dispersion velocities is satisfactory. Our crust-to-mantle transition locations and thickness are, in general, in good agreement with those inferred from the refraction models. Beneath HALM and RAYN, however, our inferred crust-to-mantle transitions contrast with a sharp discontinuity in Mooney et al. [1985] and Badri [1991] interpretations. Actually, a sharper boundary is more consistent with the sharp PpPms phase observed in the receiver function at station HALM, but not at RAYN. The uppermost crust in our models is slower than that inferred from the refraction models; actually, one expects to find low velocity near-surface material as a result of weathering fracture.

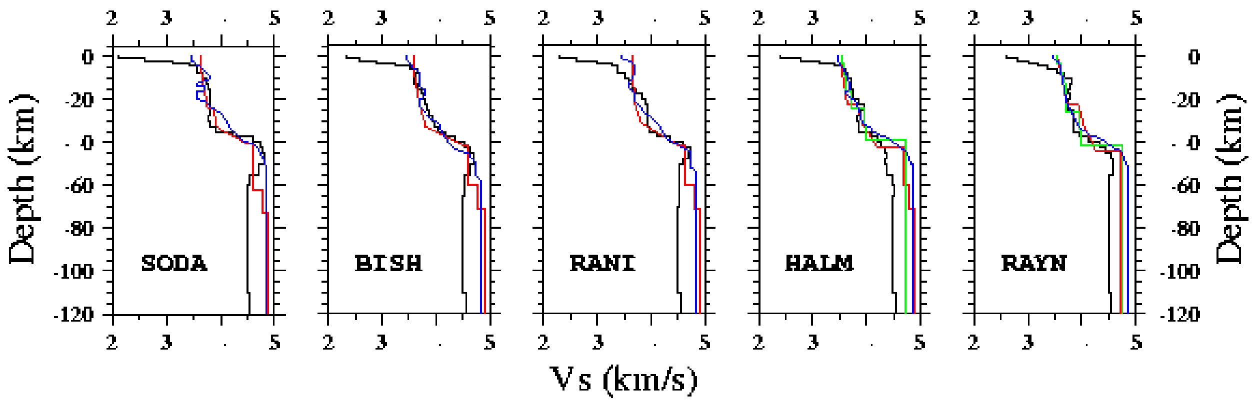


Figure 6: Comparison between the NE resulting models (black) and the refraction profile models from Mooney et al. [1985] (red), Prodehl [1985] (blue) and Badri [1991] (green).

Application to Western US

We also employ the methodology to model receiver functions and dispersion measurements beneath two broad-band stations in North America: ANMO and KNB (Figure 7). In this occasion we invert phase velocity measurements for the fundamental mode of Rayleigh and Love waves with receiver functions at two frequency bands and different ray parameters. As pointed out by Ammon et al. (1990) simultaneous inversion of waveforms with different slowness alone does not appear to be enough to remove the typical depth-velocity ambiguity in receiver function inversions. As in the Arabian Shield, data allow analysis to be performed from various backazimuths; in this application, however, we will focus on the problems posed by the unavailability of short period phase velocity measurements.

Figure 8 shows the velocity constrained inversion results at stations ANMO and KNB, the constraints being the S-wave mantle velocities from TNA model [Grand and Helmberger, 1984]. At station ANMO we observe a significant and unrealistic negative gradient at the uppermost part of the structure which contrasts with the positive and more realistic gradient obtained in the same depth range beneath KNB. This different behavior is probably caused by the different suitability of the starting model (a constant 8 km/s P-wave velocity region over PREM) combined with the lack of constraints from our data. As it happened with the upper mantle structure, this unlikely structure could be trading-off with the remaining of the model, and independent information to constraint that part of the profile could be required. We also observe that some arrivals within the 1-4 s time window are not fitted; these arrivals are associated to upper crust structure, where the inversion procedure has imaged a negative gradient.

Figure 9 shows the inversion results at station ANMO when additional upper crust constraints are considered. The additional constraints simply consist of forcing the uppermost layer to have a S-wave velocity of 2.5 km/s, which is more realistic, and the negative gradient is removed. The fit to the receiver function does not show major changes, and the arrivals in the 1-4 s time window are still not fitted. The match to the dispersion velocities is still good but somewhat underpredicted in the short period range. Additional information from local dispersion velocities or from local S-wave arrivals could provide more realistic constraints. It is important to note, though, that Figure 9 demonstrates that this lack of absolute velocity information in the uppermost structure does trade-off with the remaining of it.

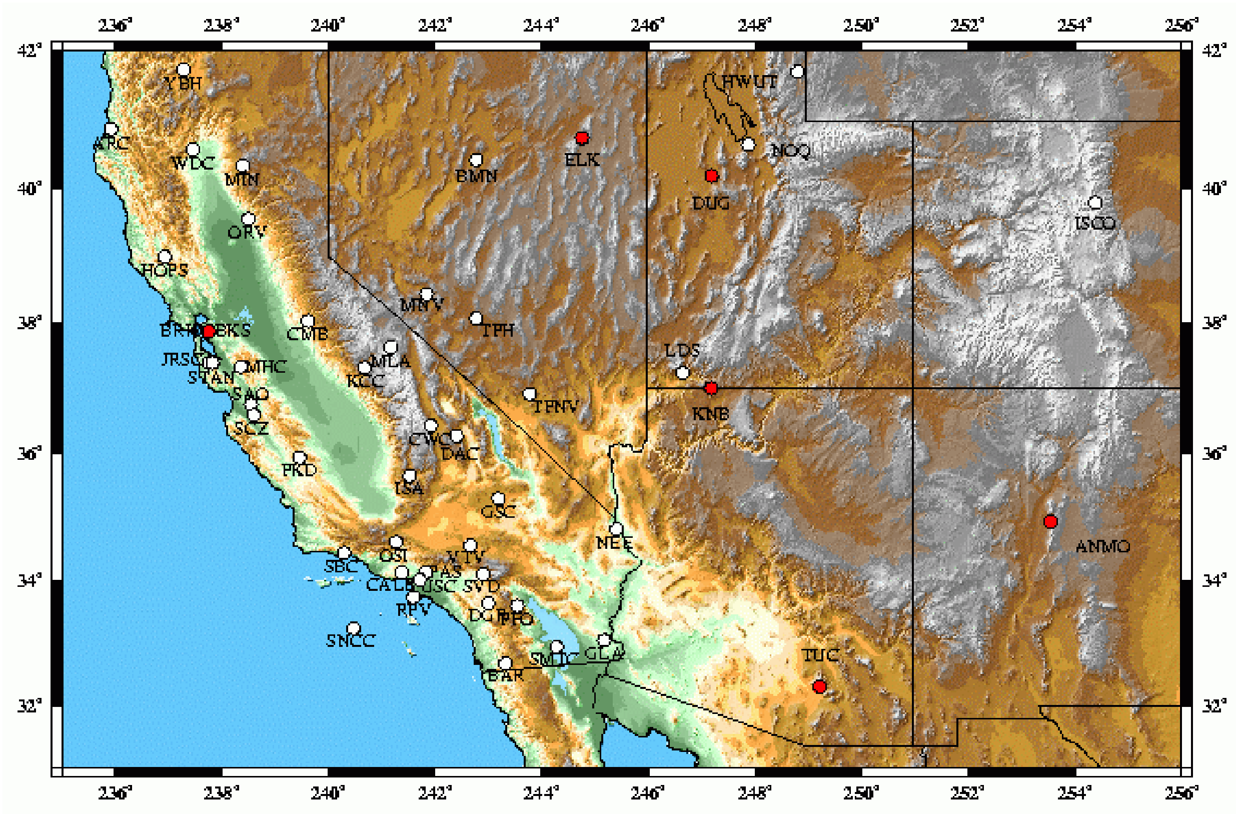


Figure 7: Topographic map of Western U.S. showing the location of various broad-band stations used in our inversions for earth structure.

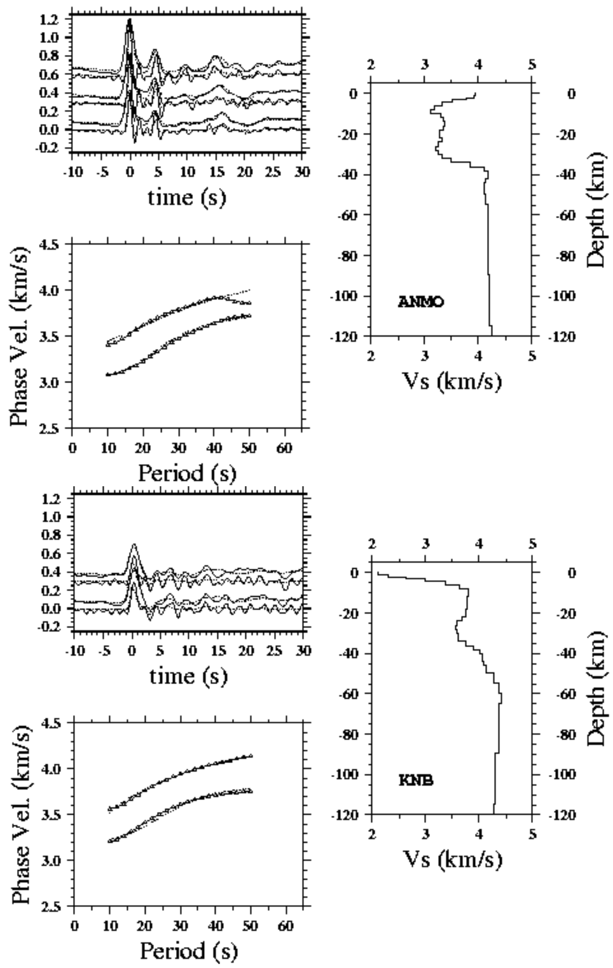


Figure 8: Inversion results at stations ANMO (left) and KNB (right) from the combination of phase-velocity dispersion measurements and receiver functions at different incidence and frequency contents. At ANMO the upper crust is imaged as an unlikely negative gradient as a consequence of the lack of absolute velocity constraints from the short-period dispersion values.

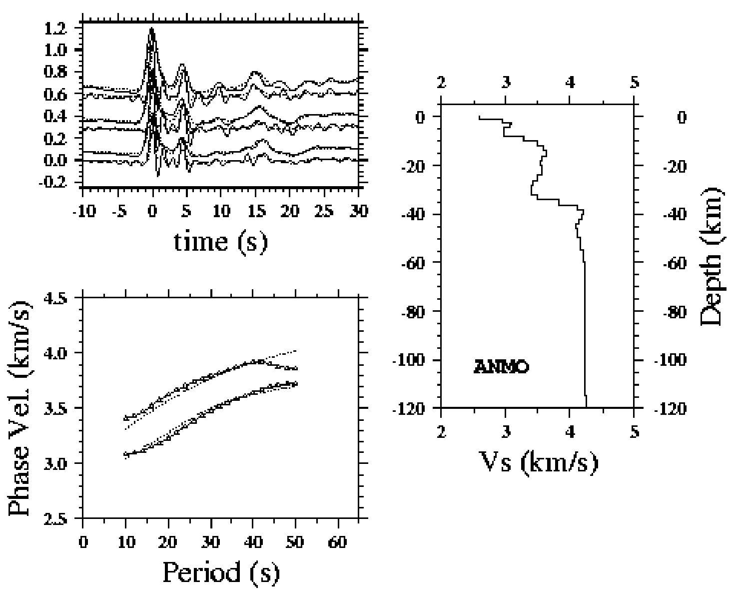


Figure 9: Inversion results for station ANMO forcing the top layer to be 2.5 km/s shear-wave velocity.

CONCLUSIONS AND RECOMMENDATIONS

The combination of surface wave dispersion data and receiver functions provides constraints on the shear velocity of the propagating medium that improve those provided by either of the data sets considered separately, and helps to avoid overinterpretation of single data sets. We also show that this combination cannot unambiguously resolve the fine structure of the upper mantle, although this will depend on the bandwidth considered for the dispersion data set. When no long period information is availble, independent information must be provided during the inversion process to insure a reasonable upper mantle in the model, since allowing the inversion to place an unlikely structure affects the estimates of the lower crust velocities. When no short period dispersion velocities are available, the upper crust velocity information contained in the main peak of the receiver function data may not suffice to constrain that part of earth, and independent constraints may be also required.

Key Words: Surface wave, receiver function, crustal structure, algorithms

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